RNN-based Phase Unwrapping for Enabling Vital Parameter Monitoring with FMCW Radars

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Abstract. *Application of radar technology enables remote breathing and heart rate monitoring by analyzing motion waveforms, which are reconstructed from phase signals extracted from radar-delivered data. However, nonlinear deformations introduced by phase recovery procedure make accurate motion reconstruction highly challenging, especially for millimeter-long waves that are commonly generated by state-of-the-art radar devices. In the presented paper we show that a GRU-based neural predictor is capable of correct phase unwrapping under presence of noise (originating e.g. from random subject's movements), enabling vital parameter monitoring in realistic scenarios, which cannot be accomplished using standard approaches.*
Keywords: *regression, GRU, vital parameter estimation, FMCW radar*

1. Introduction

Unobtrusive, privacy-preserving remote monitoring of basic vital signs: breathing and heart rates, becomes an attractive choice for intelligent assistive technologies. This functionality is offered by Frequency-Modulated Continuous-Wave (FMCW) radar devices, which are capable of sensing millimeter and sub-millimeter body displacements caused by respiration and skin surface micro-motion caused by blood pressure variations [1]. The latter phenomenon to be detectable, requires a use of short, millimeter-range radar wavelengths. However, reducing the wavelength poses severe problems for reconstructing micro-displacements accompanying the considered vital processes. As micro-displacements are represented through a phase of radar-produced signals, which gets wrapped if displacement magnitudes exceed a wavelength, information on motion activity becomes distorted, especially in additional presence of inevitable random, tiny body movements. This issue is rarely raised in the literature, where research typically assumes immobilizing a subject to avoid aggregating of different motion sources. However, practical utility of data analyses, performed in such a case becomes limited.

The following paper introduces a novel method for alleviating the problem of phase reconstruction, which makes reasonable estimation of basic vital parameters feasible. We propose to ground the displacement reconstruction procedure on multiple data streams that are produced by radar devices and employ a recurrent neural network as a means for nonlinear transformation that provides recovery of the actual waveform.

2. Problem formulation

Principles of FMCW radar operation and its application to vital sign monitoring can be found in several publications, e.g. [2]. The radar-monitored space is split into a set of adjacent spatial bins, and objects located in this space are represented by intermediate-frequency (IF) components of frequencies characteristic to these bins. Reconstruction of small object's displacements from FMCW radar data is based on phase information, extracted from the corresponding IF component. As phase is determined via arc-tangent operation on real and imaginary spectral components, it gets wrapped if object displacements exceed radar's signal wavelength. Another level of complexity is introduced by subject's movements and spatial extent of a body surface, which can be seen as a continuous grid of reflection points. Due to movements, these points perpetually change their locations, producing a time-dependent mixture of arbitrary-phase signals that arrive at radar receiving antennas. As tracking of vital activity-related displacements is commonly based on a simple model of a single reflecting point, the real case scenario, involving presence of a reflecting surface combined with movements that are unrelated to vital processes significantly impedes accurate recovery of location-related information from spectra. Therefore, to expect reasonable reconstruction of body surface displacements, on needs to resort to complex nonlinear data processing methods.

The problem with correct phase unwrapping using the standard approach (detection of phase jumps that exceed some adopted threshold level), when respiration activity interferes with subject's movements, has been depicted in Fig.1. The presented scenario assumes that signals are registered using 77GHz FMCW radar (approximately 3.9 mm wavelength) and shows actual and reconstructed phase waveforms for idealized respiratory activity of magnitude 1.5 cm, without (red plots) and with (blue plots) Gaussian motion noise with zero mean and 0.5 mm standard deviation (originating e.g. from chest orientation fluctuations). As it can be seen, the reconstructed phase does not provide the correct basis neither for breathing or heart rate estimation. Although the adopted noise model is highly simplified, it is not far from reality, as similar structures can be observed in unwrapped phase waveforms for actual recordings.

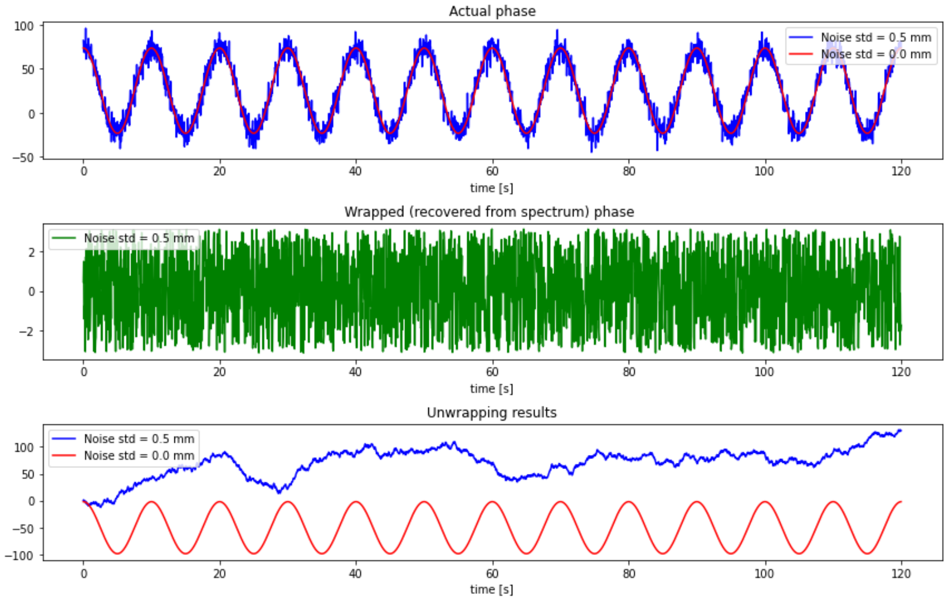

Figure 1. Phase unwrapping problem for respiratory activity monitoring, resulting from random subject's motion. Source: own work.

3. The proposed method

To alleviate the presented difficulties with correct reconstruction of small body surface displacements, we propose to fully exploit capabilities offered by majority of current FMCW radars, which typically contain several receiving (RX) and transmitting (TX) antennas. Since antenna locations are different, one can expect that phase shifts that exist between different RX/TX antenna pairs, might facilitate reaching valid consensus in reconstruction of actual object location. Therefore, the considered problem can be viewed as a prediction of a scalar sequence (phases reconstructed at subsequent time instants) from a sequence of multidimensional observations, where the dimension of input vectors is determined by the product of the number of receiving and transmitting antennas.

Solution to the considered problem requires inversion of highly nonlinear data transformations, so one needs to resort to machine learning methods as the only reasonable approach. We propose to apply Recurrent Neural Network (RNN), made up of Gated Recurrent Units (GRU) [3] to solve the posed prediction problem. Block diagram of the adopted computational architecture for vital-sign analysis, with the proposed GRU-based phase unwrapping module, has been presented in Fig.2.

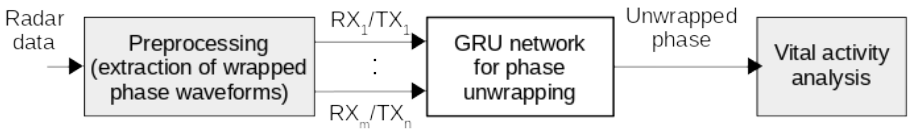

Figure 2. Diagram of the proposed vital activity monitoring algorithm. Source: own work.

4. Experiments

For data collection, the Texas Instruments IWR1443BOOST FMCW radar operating at 76-81 GHz range, has been used. To train the phase-unwrapping neural module, a dataset comprising more than ten hours of recordings of still subjects, positioned at different locations and orientations with respect to the radar, has been created [4]. Radar recordings are accompanied with reference information (targets) that has been collected using a wearable Zephyr BioHarness belt [5] that provides estimates of actual breathing and heart rates.

Of several architectures of the GRU-based neural networks tested during the experiments, the optimum balance between performance and complexity has been offered by the four-layer structure, involving one GRU layer with two units and three dense layers. The total number of parameters of the network is only 682, which makes it easy for hardware implementation. Training of the network was driven by MSE loss with additional L2 weight regularization, for 10 epochs using Adam optimizer. Prediction of output is made based on ten element-long input sequence segments in a sequence-to-sequence conversion scheme.

The network was tested on a disjoint set of recordings and it produces location estimates that serve as a good basis for accurate evaluation of respiratory-related activity. The result for unwrapping of the noisy signal presented in Fig.1 by the proposed algorithm has been shown in Fig.3. As it can be seen, it provides a robust basis for estimation of a fundamental frequency of the target waveform. In addition, average MSE results produced for the test data analyzed using the reference scheme and the proposed method, are shown in Table.1

Table 1. Phase unwrapping accuracy for the proposed and reference methods

	Reference scheme	Proposed scheme
MSE	663.8512	1.0859

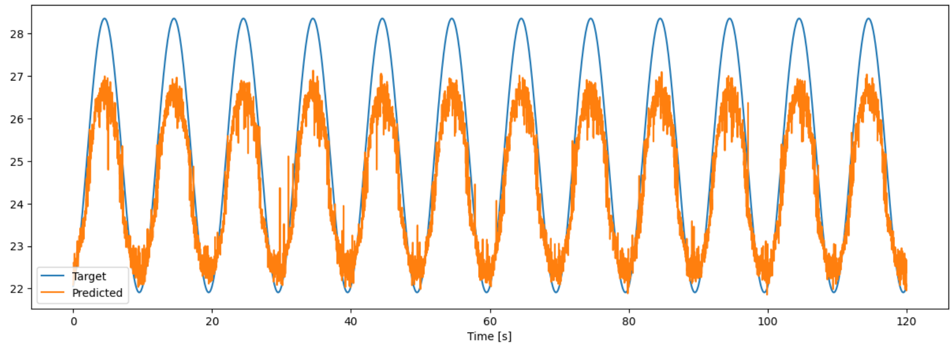

Figure 3. Result of unwrapping the simulated phase with the proposed method. Source: own work.

5. Conclusions

A novel phase-unwrapping approach that enables tracking small displacements of objects located in a space monitored by an FMCW radar, has been presented in the paper. The proposed method utilizes GRU-based recurrent neural network and offers monitoring of respiration-related motor activity in a realistic scenario, where arbitrary sources of subject's micro-movements are allowed. The only limitation of the proposed approach is a requirement that a person subject to monitoring is not 'ideally' (within 1 degree interval) perpendicular to the radar axis. As the proposed algorithm involves tiny network, it can be easily implemented in hardware, enabling delegation of intelligent computing to edge devices.

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References

[1] Anitori L., de Jong A., Nennie F., *Fmcw radar for life-sign detection*, [In:] *2009 IEEE Radar Conference*, pp. 1–6, doi: 10.1109/RADAR.2009.4976934.

[2] Jardak S., Alouini M.S., Kiuru T., Metso M., Ahmed S., *Compact mmWave FMCW radar: Implementation and performance analysis*, *IEEE Aerospace and Electronic Systems Magazine*, 2019, vol. 34, no 2, pp. 36–44, ISSN 0885-8985, doi: 10.1109/maes.2019.180130.

[3] Cho K., van Merrienboer B., Bahdanau D., Bengio Y., *On the Properties of Neural Machine Translation: Encoder-Decoder Approaches*, *arXiv:1409.1259 [cs, stat]*, 2014.

[4] Ślot K., Łuczak P., Lewandowski P., Jaśkiewicz M., Bielińska-Ślot A., *CHIST-ERA AIR - FMCW radar recordings*, (access: 12-07-2023). https://chist-era-air.iis.p.lodz.pl/

[5] Hailstone J., Kilding A.E., *Reliability and Validity of the Zephyr™ BioHarness™ to Measure Respiratory Responses to Exercise*, *Measurement in Physical Education and Exercise Science*, 2011, vol. 15, no 4, pp. 293–300, ISSN 1091-367X, doi: 10.1080/1091367X.2011.615671.